

A Superconducting Harmonic Cavity for Bunch Lengthening in the APS-U

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ASD Seminar

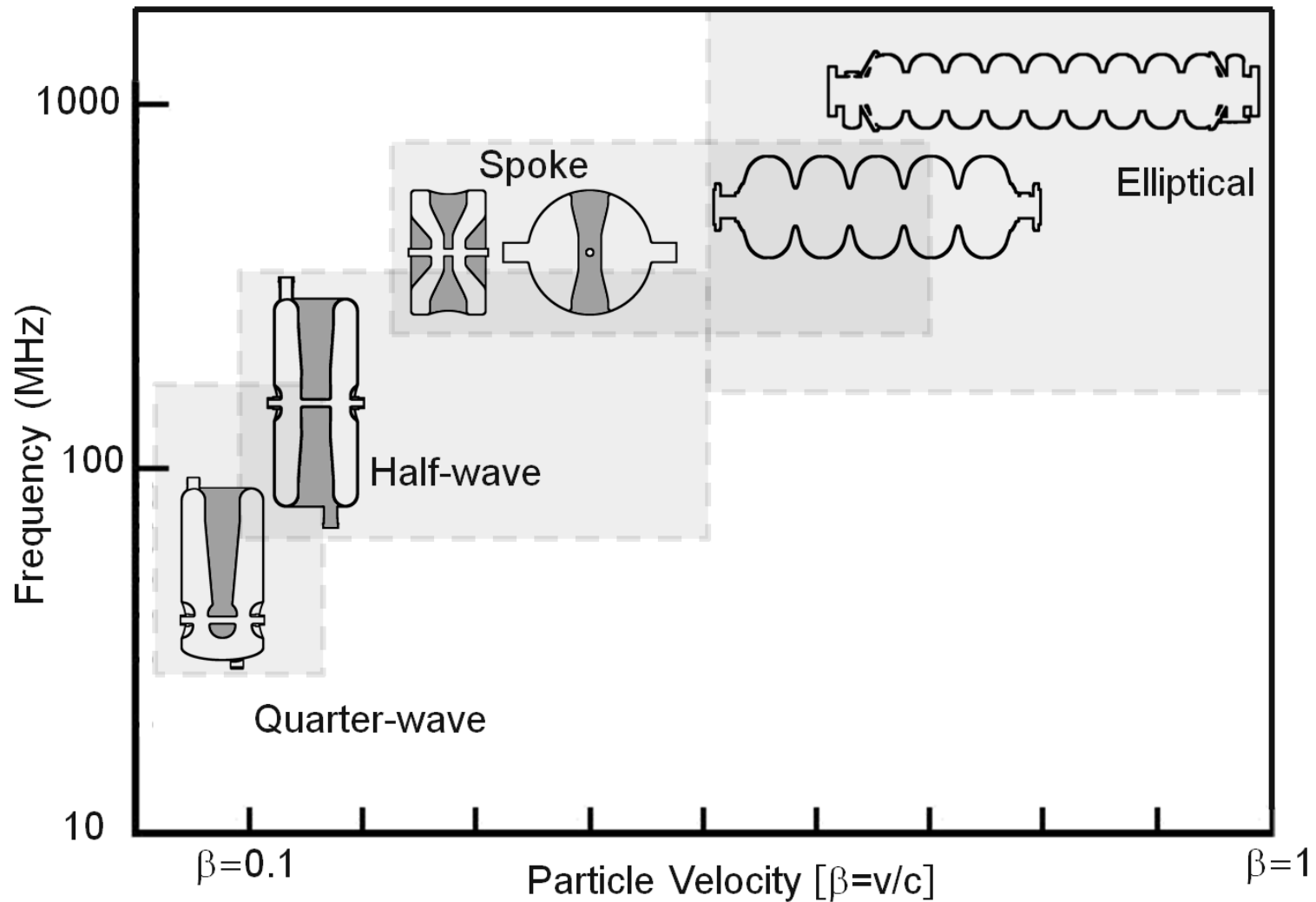
12 August 2015

Introductory Comments: A Few Milestones

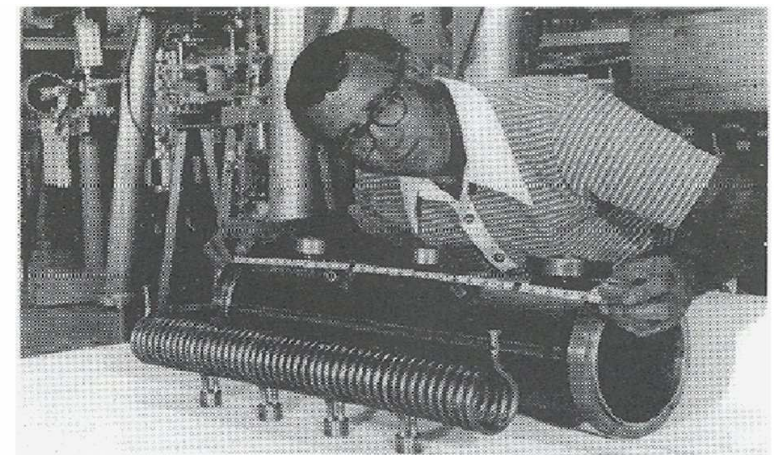
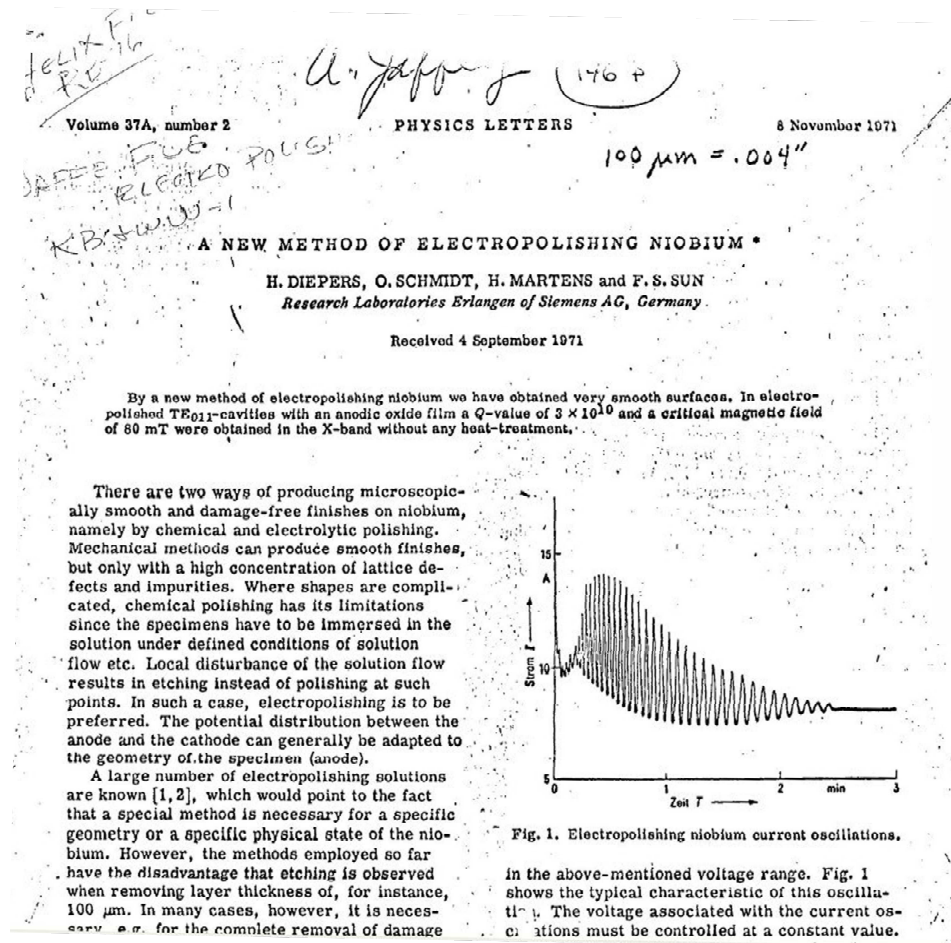
- **1911 Heike Kamerlingh Onnes discovers the effect of superconductivity**
- **1957 Bardeen, Cooper, and Schrieffer published their microscopic theory of superconductivity**
- **1961 Fairbank proposed an accelerator based on superconducting rf cavities**
 - **1964 First acceleration of an electron beam with a superconducting cavity**
- **1977 First superconducting accelerator (SCA) completed at HEPL-Stanford**
- **1978 First superconducting heavy-ion accelerator completed at Argonne Physics Division**



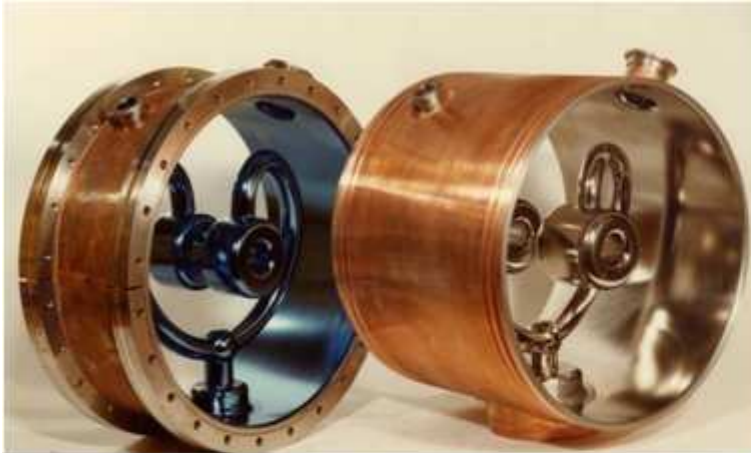
Practical Superconducting Cavity Geometries Spanning the Full Range of Velocities



ANL Work in the Early 1970's: Helical Nb Resonator Intended for a Heavy-Ion Linac



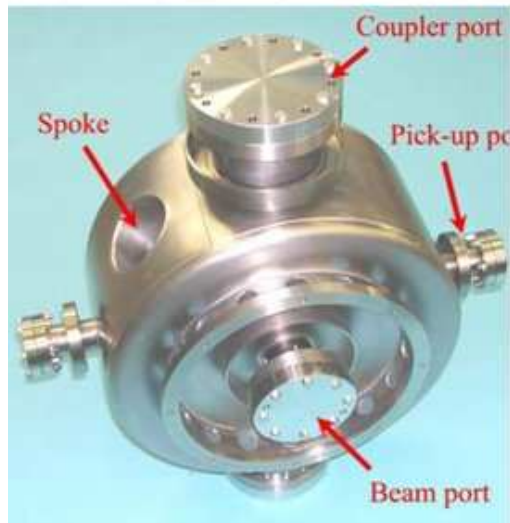
Quarter-wave Cavities



Half-wave Cavities



Spoke Cavities

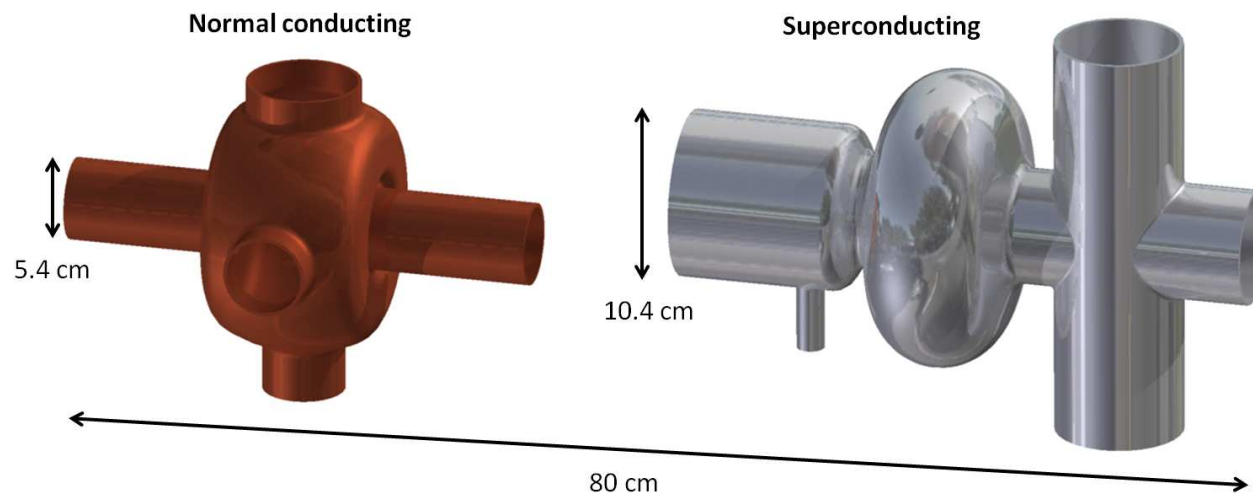


Why Use a Superconducting Cavity for APS-U?



Properties of Superconducting Cavities

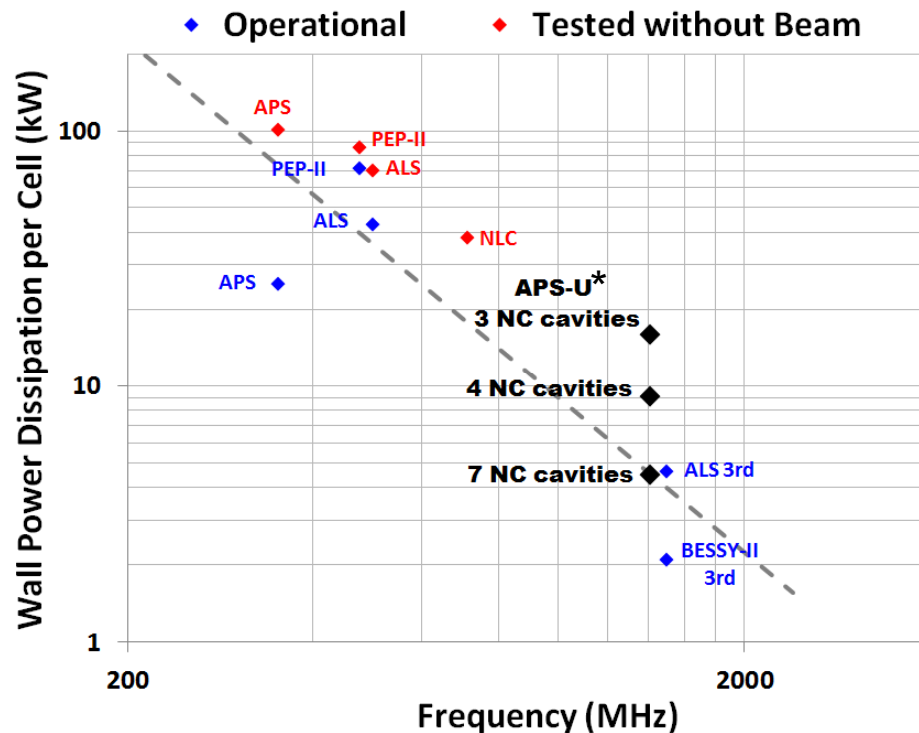
- Large acceptance
- Low RF losses
- (Suitably) good mechanical properties
- Operate at high accelerating gradients



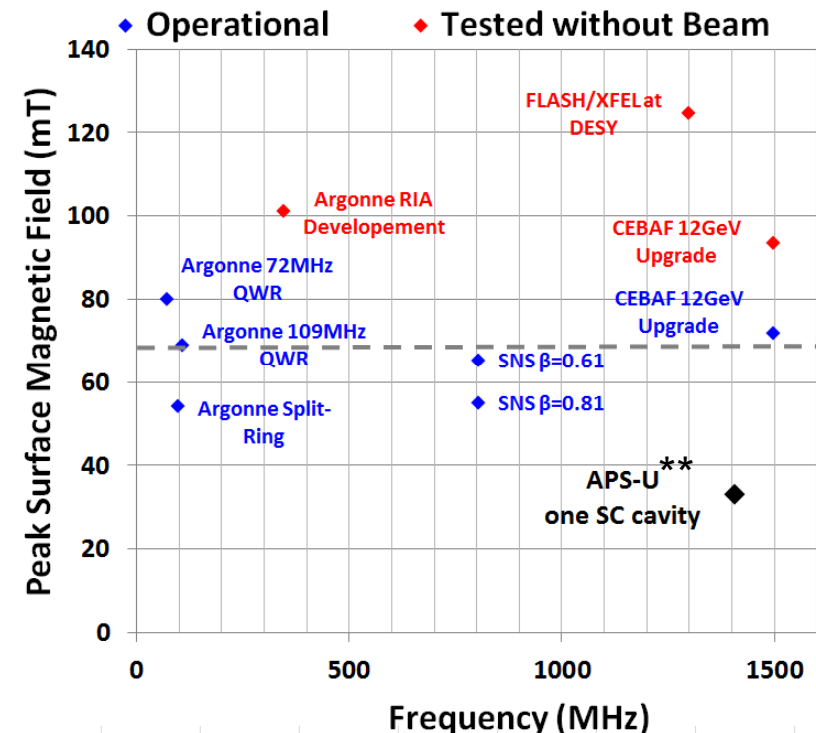
Possible Single-cell RF Cavities for 1.4 GHz

Normal Conducting and Superconducting Cavity Performance

Normal Conducting Cavities



Superconducting Cavities



*assumes a copper cavity with geometry similar to Advanced Light Source (ALS) 3rd harmonic cavity, but scaled to a frequency of 1.4 GHz

**assume a 1.4 GHz SC cavity with the 'TESLA' shape



Spectrum of *Trapped* Higher-order Modes for a 1.4 GHz (ALS-style) Normal Conducting Cavity

- CST used to calculate mode frequency, R/Q , Q_0
- Typical normal conducting cavities will have a fairly complex set of trapped higher order modes
 - A set of plunger tuners used to ‘detune’ HOMs
- The superconducting structure has no trapped monopole or dipole higher order modes

CST calculated modes below cutoff assuming copper ALS-style cavity scaled to 1.4 GHz; yellow indicates that the impedance exceeds stability threshold

f (GHz)	Q ₀	R/Q (Ohm)	R _s (Ohm)	Mode
1.404	2.5E+04	7.6E+01	1.9E+06	f ₀ : TM 010
2.147	2.3E+04	3.7E+01	8.6E+05	TM 011
3.160	2.5E+04	3.1E+00	7.9E+04	TM 020-1
3.461	4.8E+04	3.6E+00	1.7E+05	TM 020-2
3.776	2.1E+04	9.7E-01	2.1E+04	TM 021
f (GHz)	Q ₀	(R/Q) _T (Ohm/m)	R _T (Ohm/m)	Mode
1.780	2.0E+04	4.1E+01	8.4E+05	TE 111 Horizontal
1.814	2.1E+04	4.7E+01	9.9E+05	TE 111 Vertical
2.122	2.0E+04	1.0E+03	2.0E+07	TM 110 Vertical
2.193	1.2E+04	3.3E+02	4.0E+06	TM 110 Horizontal
2.710	2.1E+04	1.2E+03	2.5E+07	TM 111 Vertical
2.714	2.0E+04	1.2E+03	2.4E+07	TM 111 Horizontal
3.013	3.0E+04	5.5E+01	1.7E+06	TE 112 Horizontal
3.015	2.9E+04	7.0E+01	2.0E+06	TE 112 Vertical

Why Use a Superconducting Cavity for APS-U?

- **Requires a single cavity**
- **Meets APS-U requirements with ample margin on performance**
- **Straightforward handling of HOMs**
 - Lower impedance presented to beam
- **Flexibility to adjust loaded quality factor**
- **These are unique to the superconducting cavity**



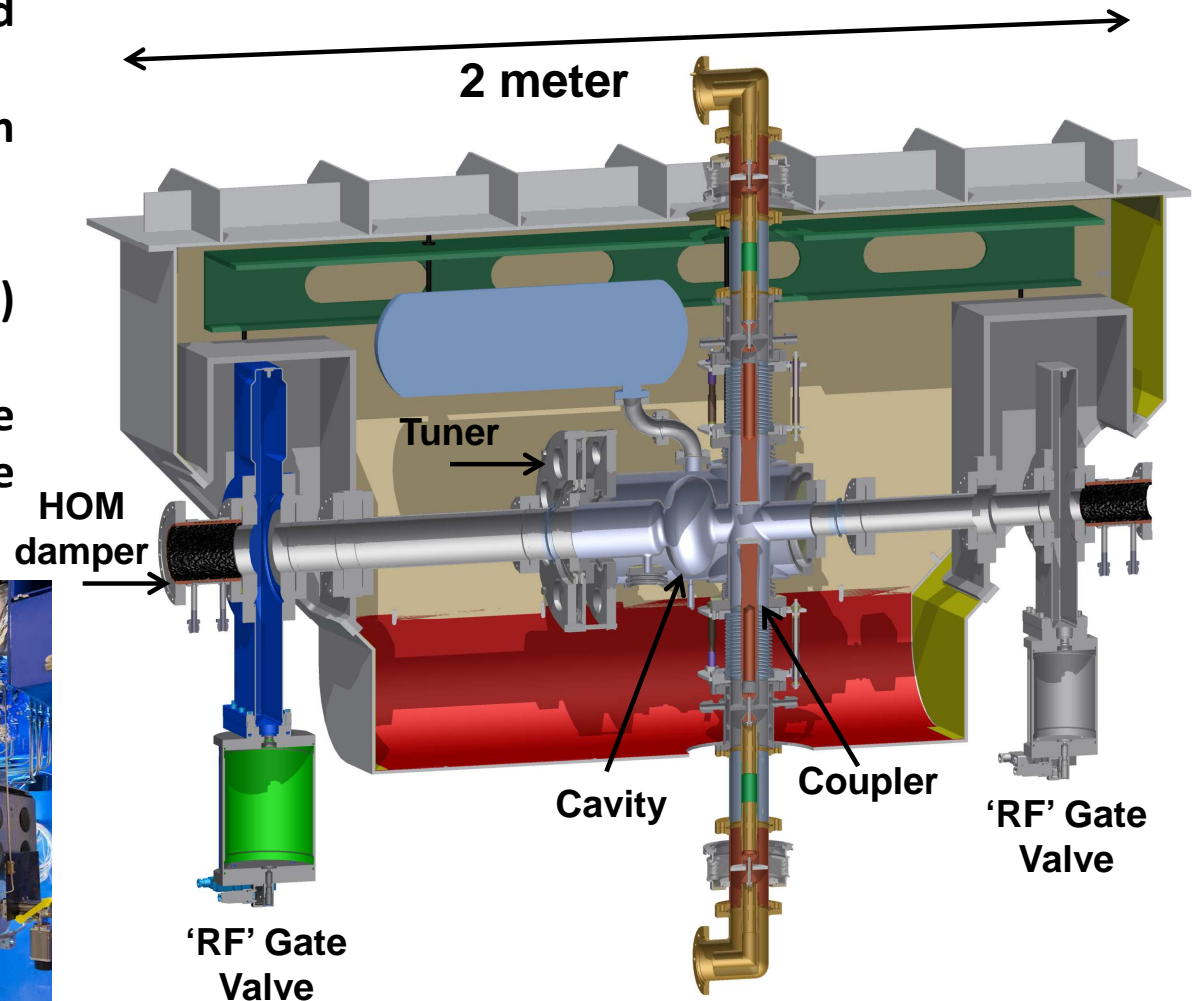
Hardware for the APS-U Harmonic Cavity



Conceptual Design for a Bunch Lengthening System

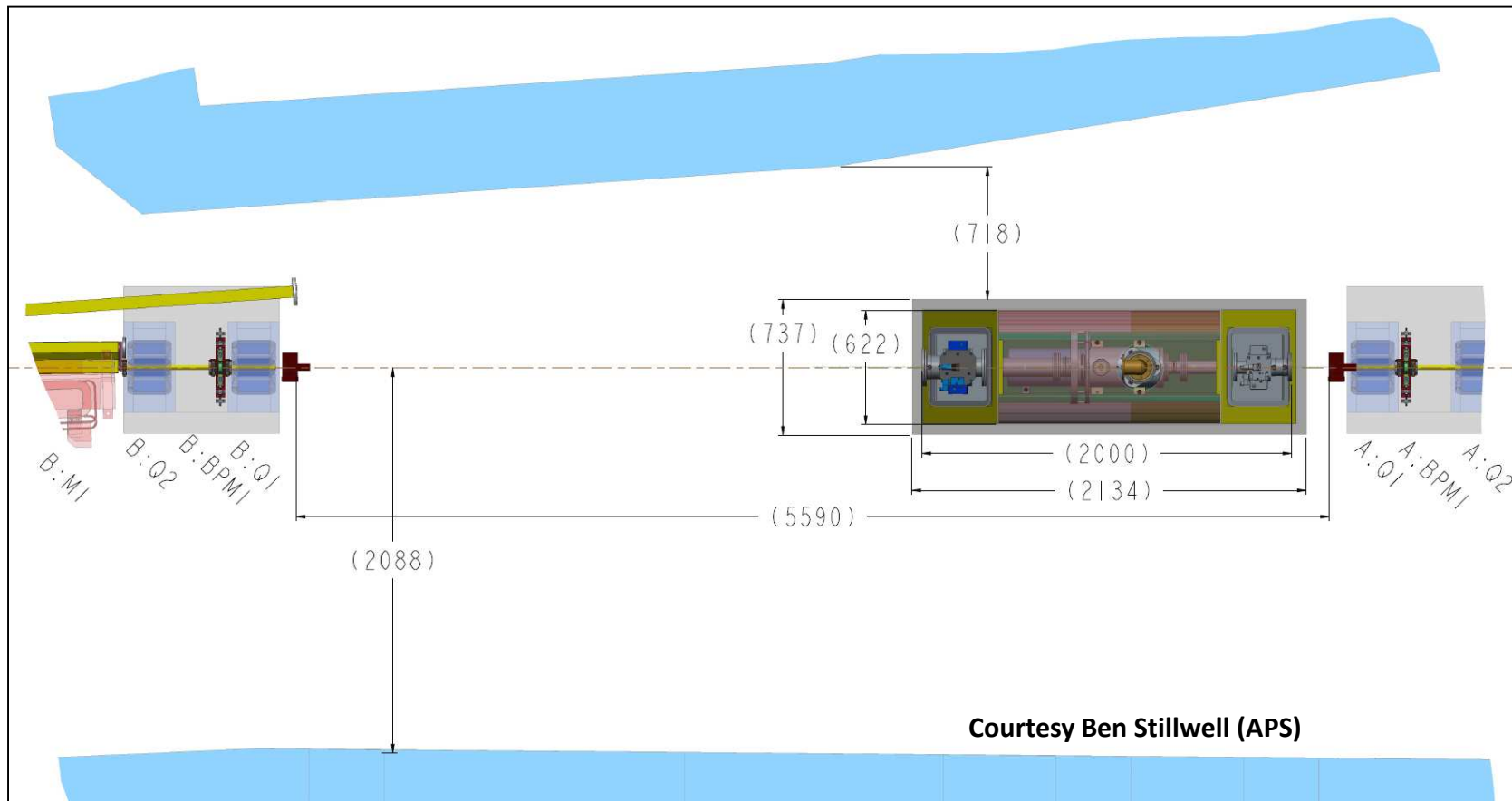
A single higher-harmonic cavity in a top loading cryomodule

- A cryomodule with cavity and ancillaries cooled to 4 Kelvin
- One SRF cavity – field driven by the beam
- Two power couplers
- A mechanical (pneumatic) tuner
- A pair of room temperature beamline higher-order mode dampers



HHC Cryomodule Footprint in a Generic APS-U Straight Section

Plan View with Dimensions in mm



Parameters for a 4th Harmonic SC Cavity

Cavity operating parameters are modest by today's standards even for the 'relaxed' operating temperature of 4.5 K

	Parameter	Symbol	Unit	Value
Harmonic Cavity	Operating Temperature	T	K	4.5
	R/Q	r/Q	Ohm	109
	Cavity Quality Factor	Q_0		2×10^8
	External Q	Q_{ext}		$2 \times 10^5 - 2 \times 10^7$
	Cavity Loaded Bandwidth	Δf_{BW}	kHz	5.4
	Detuning Frequency	δf_r	kHz	15
	Cavity Resonant Frequency	f_r	MHz	1408
	Beam-Induced Voltage	V_b	MV	0.90
	Detuning angle	ψ_h	degrees	78.9
	Beam Loss Power	P_b	kW	32
	Cavity Wall Loss Power	P_{wall}	W	35
	Peak Surface Electric Field	E_{peak}	MV/m	17
	Peak Surface Magnetic Field	B_{peak}	mT	35



Overview of R&D Plan for Important Hardware

The cavity and subsystems are being built largely on demonstrated technology; However, detailed designs for every subsystem are new.

Risks are those associated the cost and delay due to re-work, e.g. a cavity with a defect, coupler manufacturing or durability problems.

Some technical risks (e.g. those associated with high order modes) are best mitigated by an 'in ring' test

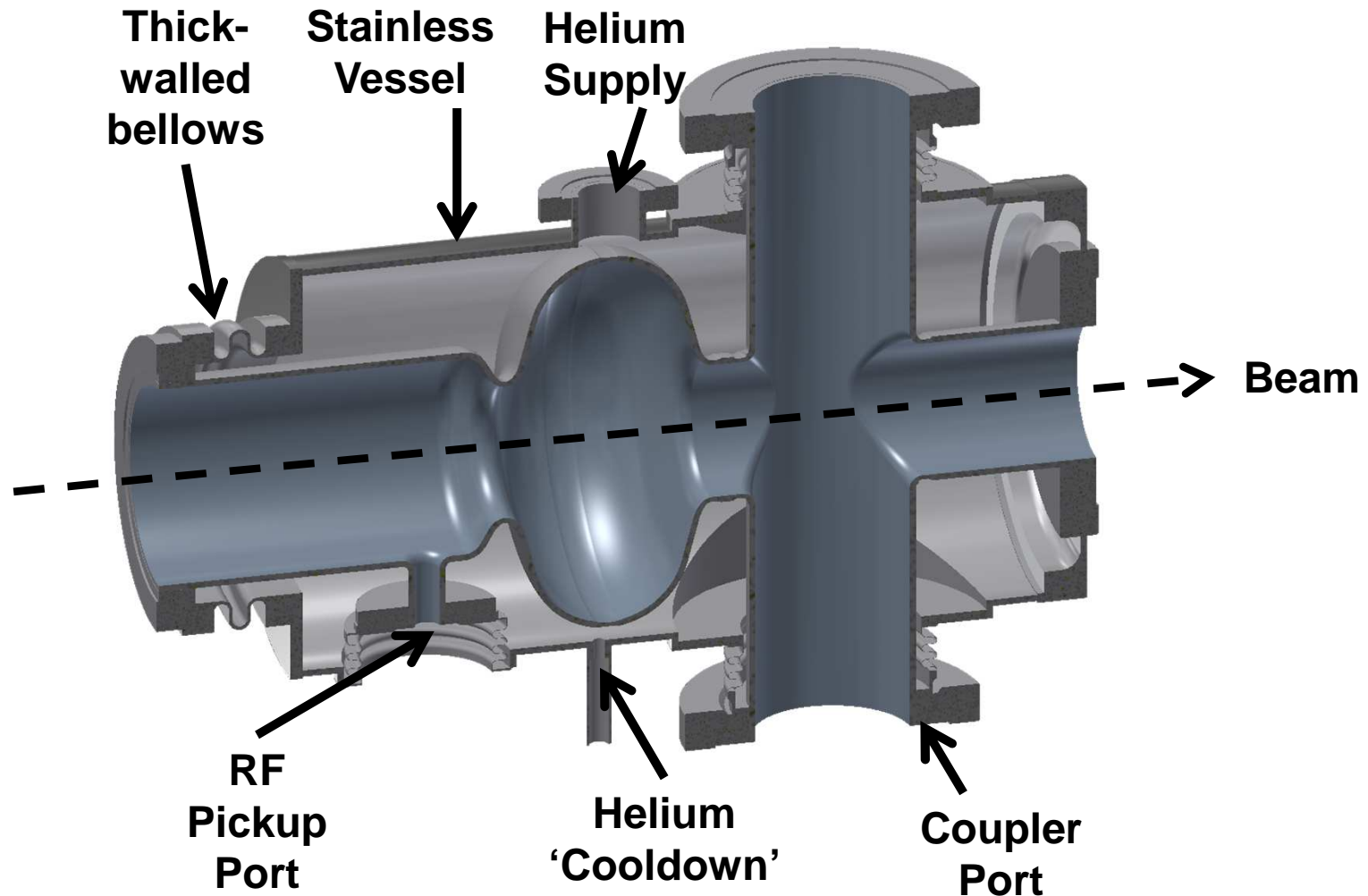
The highest priority development items are:

- **20 kW CW co-axial RF power couplers**
- **Superconducting RF Cavity(s)**
- **Higher order mode dampers**



Harmonic Cavity - Section View

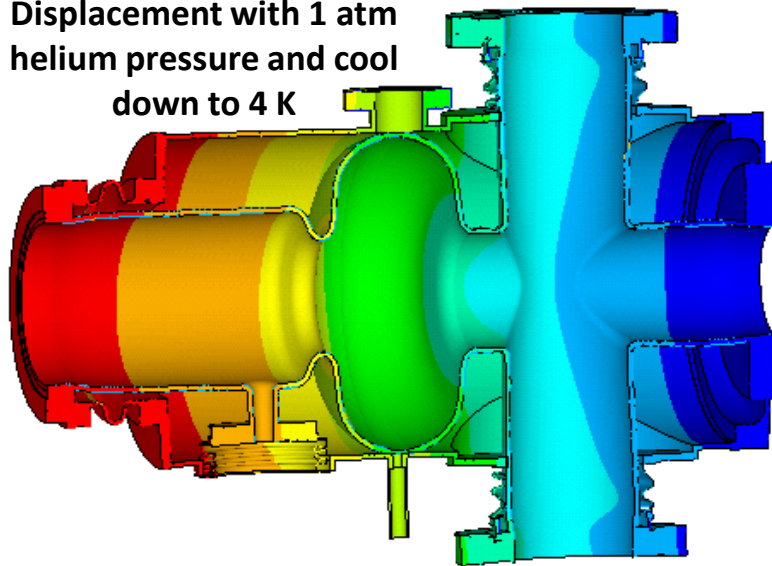
Cavity from 3 mm thick high-purity niobium sheet housed in an (ASME code stamped) stainless steel helium vessel



Mechanical Analysis for Higher Harmonic Cavity

Parameter	Unit	Value
Slow tuner sensitivity	Hz/lb-f	-163
Tuning range	kHz	600
Helium Pressure Sensitivity	Hz/mbar	6.3
Frequency Shift 300 K to 4 K	kHz	1066
Conditional for Plastic Collapse	PSID	>60

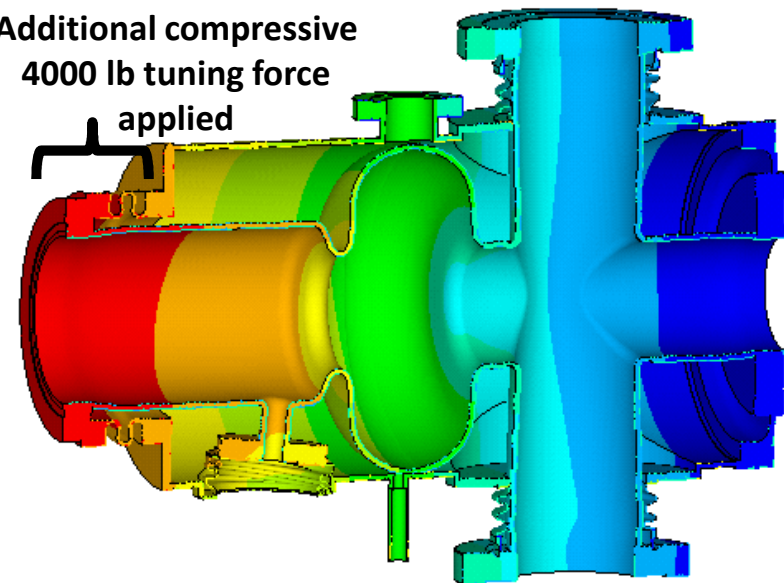
Displacement with 1 atm
helium pressure and cool
down to 4 K



.022 0 -0.026

Axial Displacements - inches

Additional compressive
4000 lb tuning force
applied



.028 0 -0.033

Axial Displacements - inches

Recent Progress on APS-U Harmonic Cavity

**Finish machined ports shown
niobium tube copper brazed into
a stainless flange**



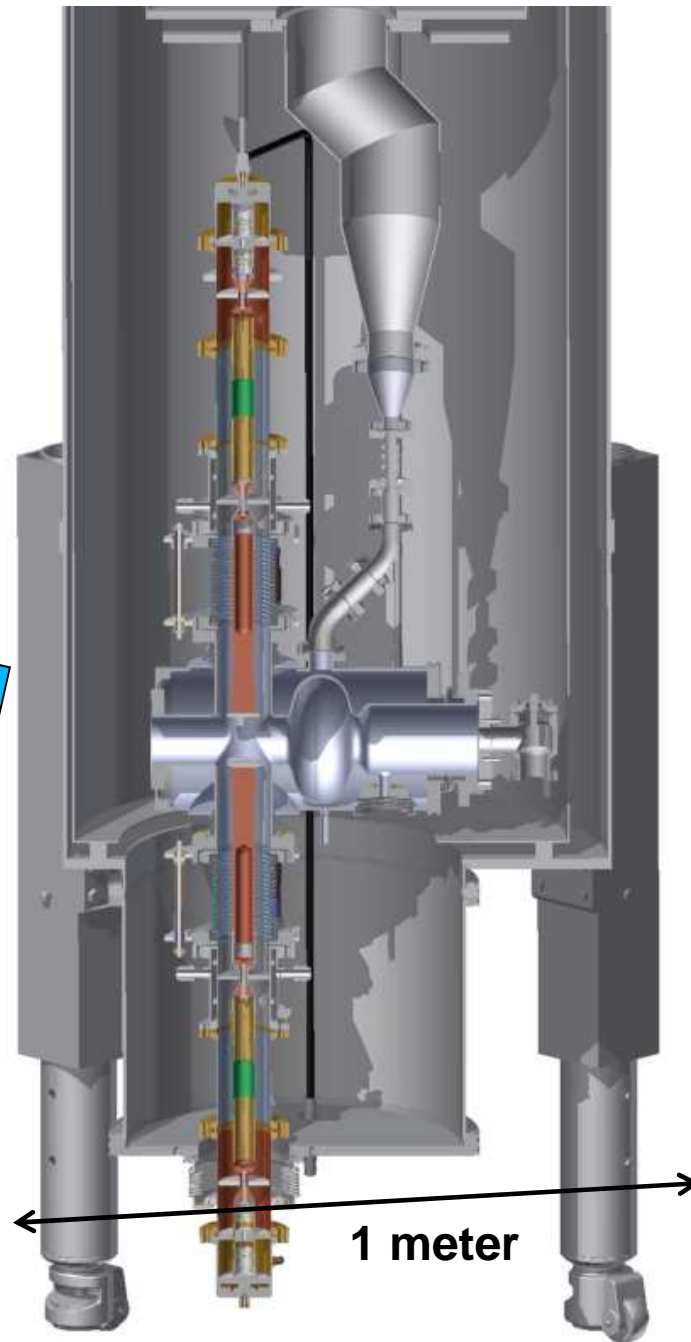
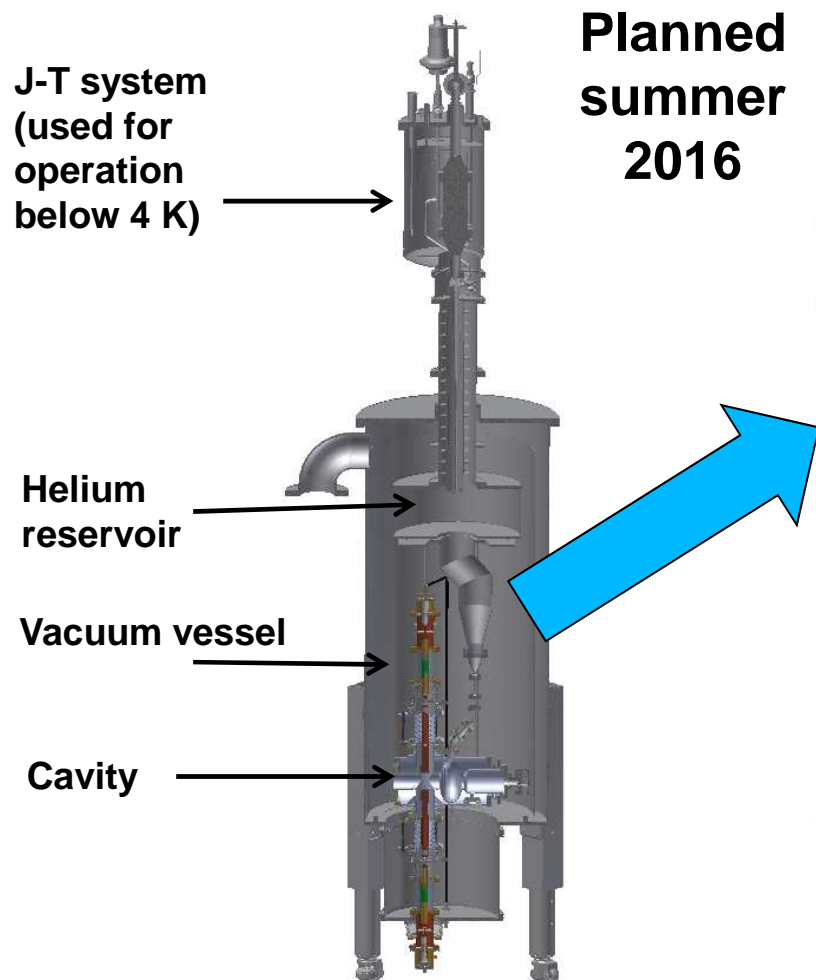
AES tooling for niobium forming



ANL-supplied stainless-to-niobium braze assemblies

Cavity Cold Testing

Layout in ANL Test Cryostat #2

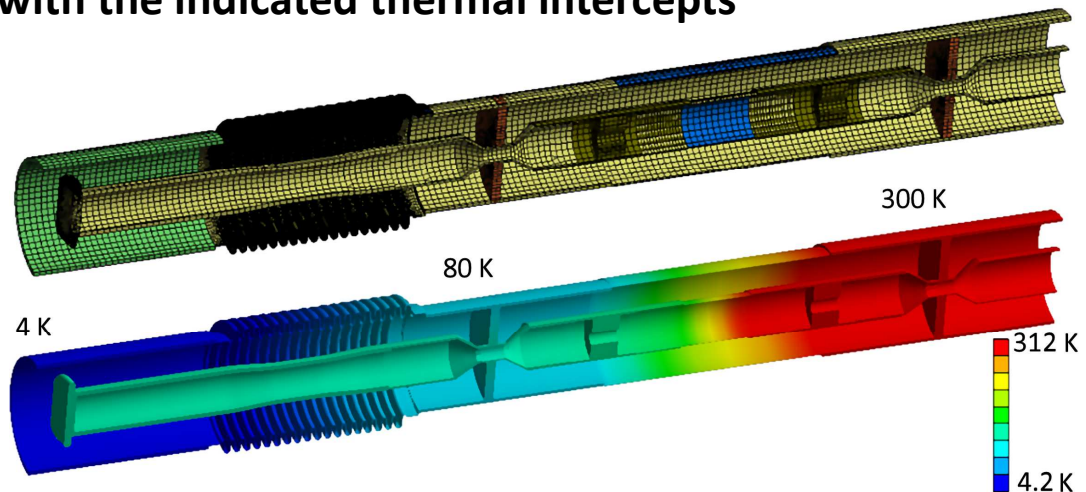


20 kW Power Coupler

- No existing design is directly suitable for 20 kW CW, 20 dB variable coupling
 - Note - difficult to provide 20 dB variability with a waveguide coupler
- However, essentially all techniques are well established
 - ATLAS, SNS and Cornell ERL Injector
- RF/Thermal/mechanical simulations for an 77 mm diameter, 50 Ω , coaxial design have been performed in ANSYS and CST MWS



ANSYS simulation of coupler temperature distribution of operation with 20 kW, 1.4 GHz in travelling wave mode with the indicated thermal intercepts



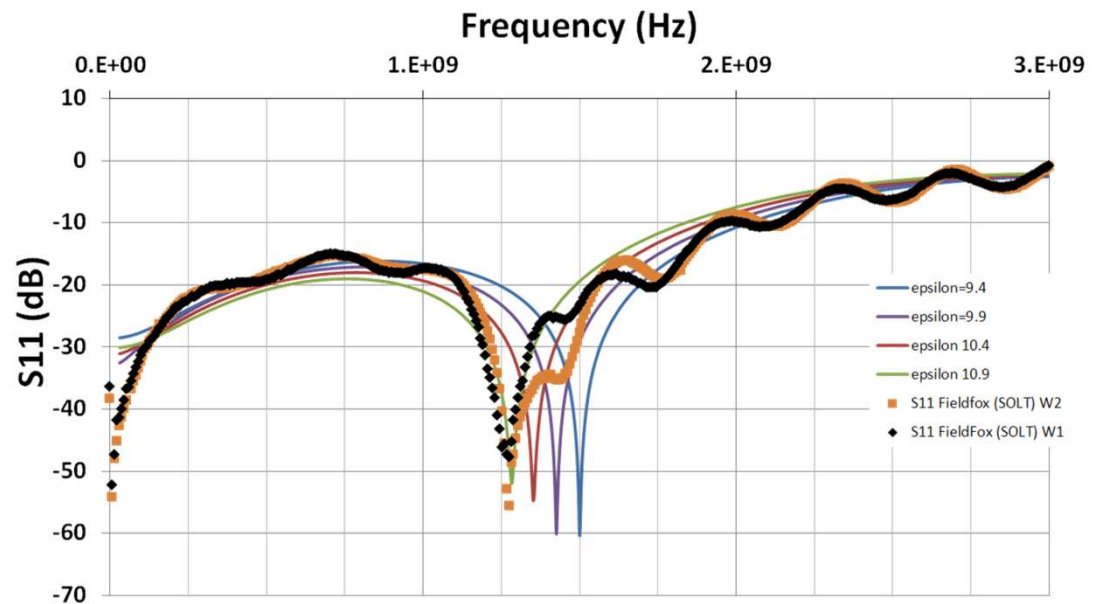
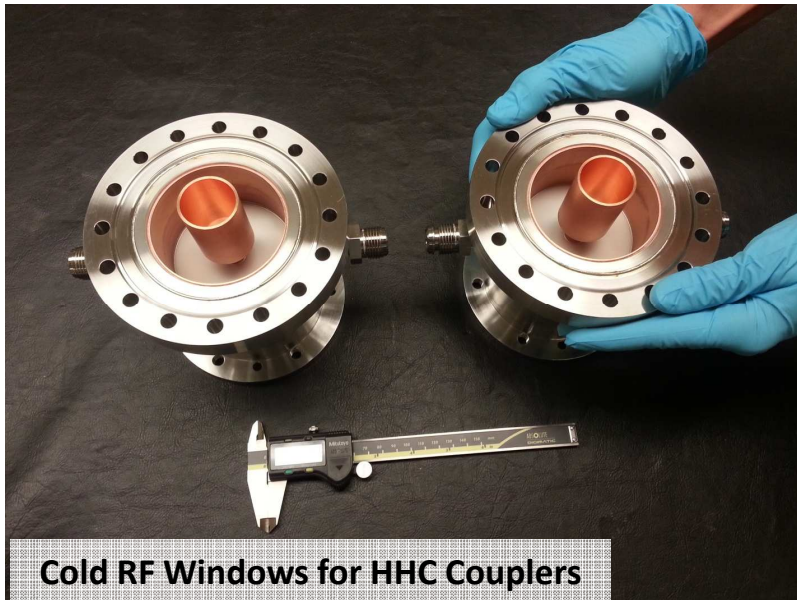
20 kW Power Coupler: Parameters

Parameter	Unit	Value
Type		Coaxial
Line impedance (nominal)	Ω	50
Outer conductor diameter	cm	7.7
Stroke, axial	cm	4
@20 kW		
Power loss to 300 K	W	74
Power loss to 80 K	W	94
Power loss to 4 K	W	2



Cold Testing of Power Coupler RF Windows

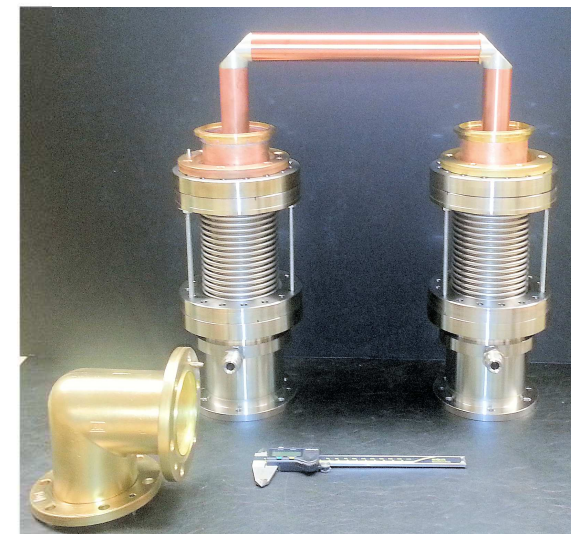
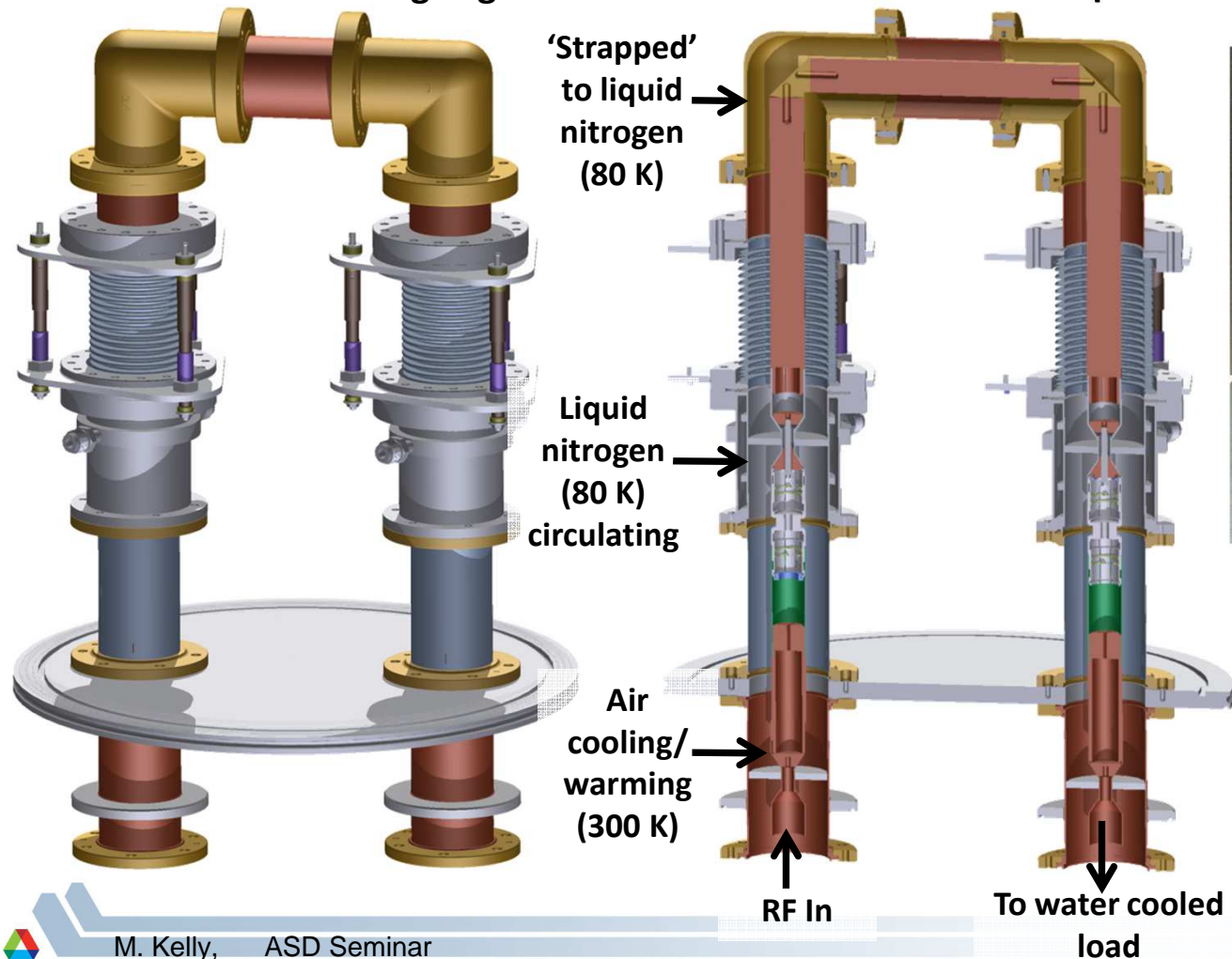
- Two cold windows are designed and built
 - High-purity alumina 'donut' brazed into copper inner and outer conductors
- A important feature is the matching section (hourglass-shaped central conductor) optimized for frequencies near 1.4 GHz



Measured and calculated reflection coefficients

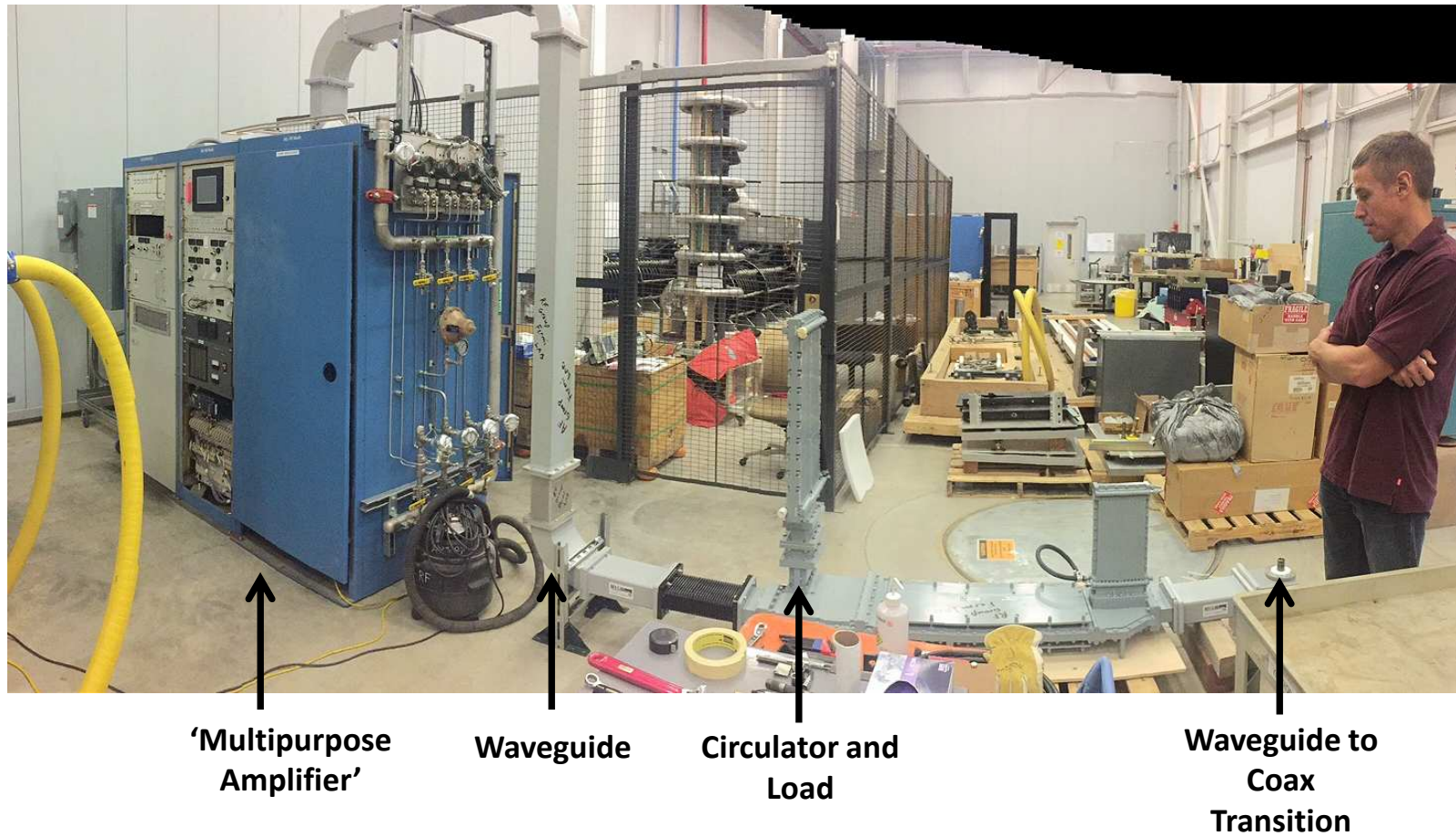
Power Coupler Testing - Fall 2015

- High-power 20 kW testing with an 'available' 1.3 GHz RF amplifier
- Components will be outfitted with thermometry and heaters to perform calorimetry, directional coupler
 - New GaAs light-guide thermometers to measure temperature on central conductor



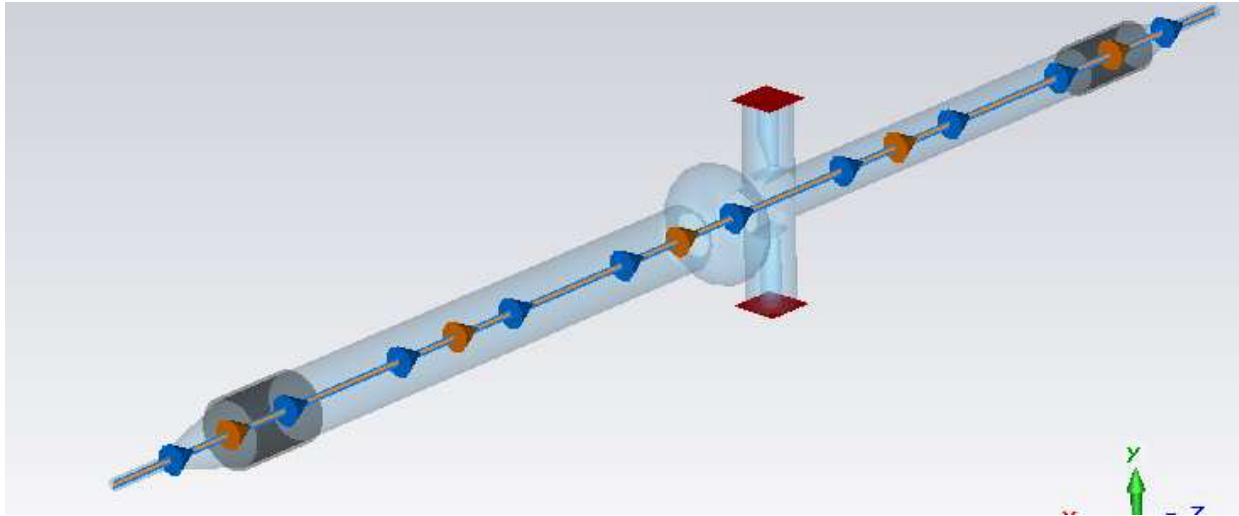
Power Coupler Testing - Fall 2015

20 kW 1.3 GHz Amplifier to be Test at APS, then Moved to 203



**Work of Doug Horan and
his crew**

Higher Order Mode Damping



A charged particle moving along the beam axis interacts with the cavity and all other components

Consider excitation of the TM₀₁₁ higher-order mode in APS-U Harmonic Cavity

- Charge per bunch $q_0 = 15.3$ nC, total current $I_b = 0.2$ A
- Bunch repetition rate = **13 MHz**
- Cavity HOM parameters: $r/Q_{\text{TM011}} = 20$ Ohm, $f_{\text{TM011}} = 2.64$ GHz **$\Delta f = 26$ MHz**
- Deposited Power: $P_{\text{TM011}} = \frac{\omega_{\text{TM011}}}{4} \frac{r}{Q} q_0 I_b = \sim 250$ W

The bandwidth is of the same order as the bunch repetition rate so that one expects appreciable high-order mode power

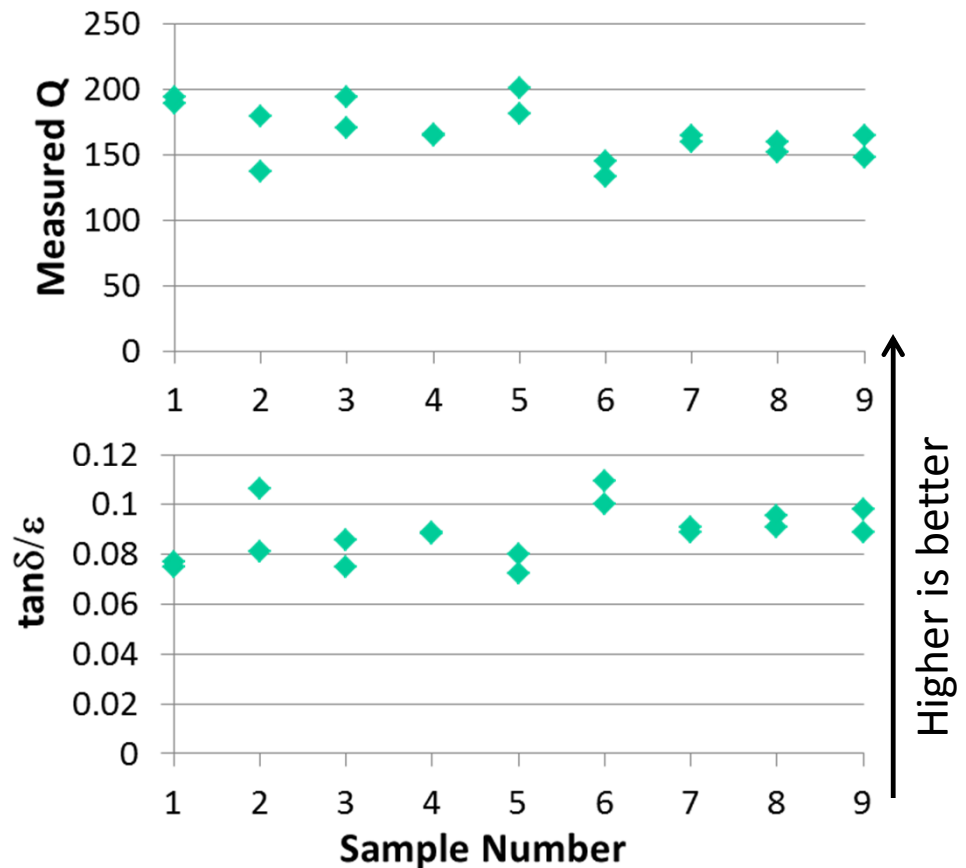
R&D Plan for Higher Order Mode Dampers

The technique and material chosen based on discussions with Cornell and their work on the ERL injector cryomodule. Thermal/mechanical/electrical studies have been performed to experimentally measure the rf loss properties, electrical and thermal conductivities

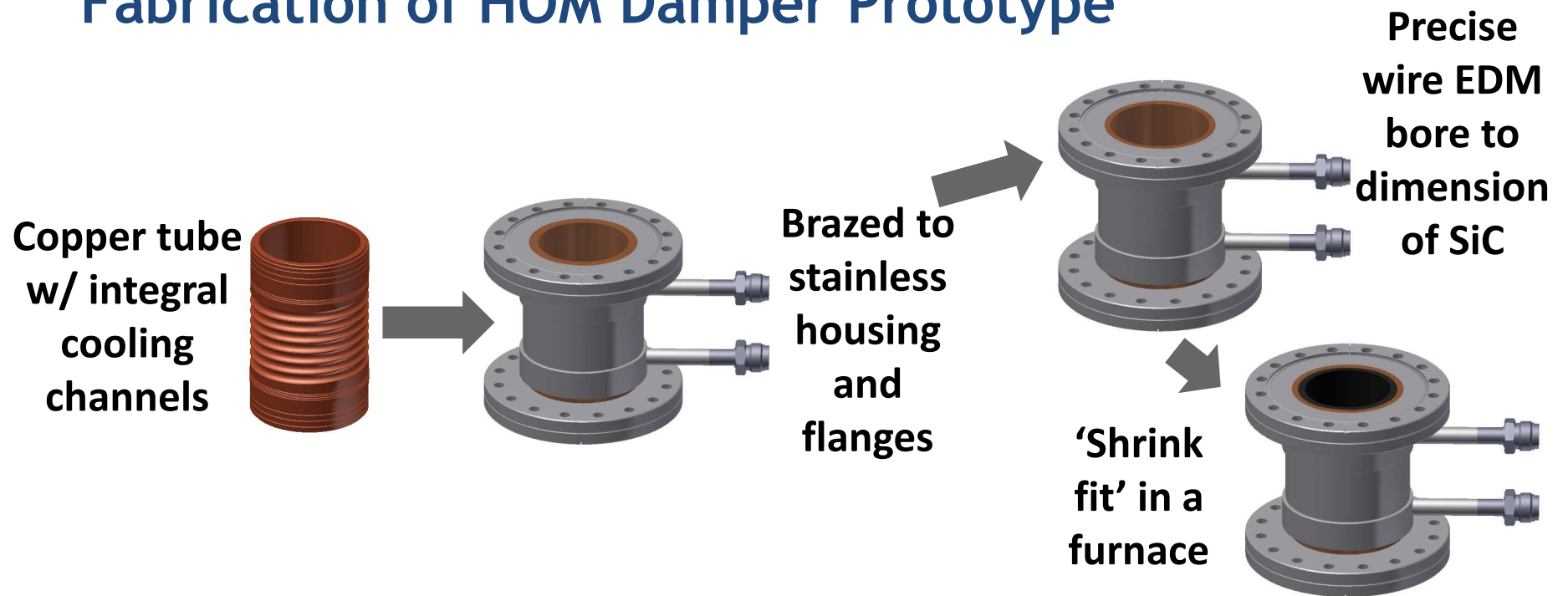
- Tests on Coorstek 35 samples and cylinders show high rf losses and good room temperature electrical conductivity



Aluminum Pillbox Cavity
Frequency TM011 = 2.7 GHz
 $Q_{\text{cavity}} = \sim 3000$



Fabrication of HOM Damper Prototype



Summary

- A superconducting cavity is the right choice of technology for a bunch lengthening system for the APS-U
 - Will, of course, provide the critical benefit to APS users of increased beam lifetime
- R&D for the cavity, couplers and higher order mode dampers will address the following:
 - Cavity fabrication and 4.5 Kelvin operation (rf losses), microphonics, tuning
 - Most aspects of coupler operations addressed in high-power @ 1.3 GHz
 - Variable coupler Qext when tested with cavity
- An 'in ring' test would be required to perform realistic tests on the damping of high-order modes

